

# NEW RESULTS FROM SUPER-K AND K2K

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Representing the Super-Kamiokande and K2K Collaborations

## ABSTRACT

This paper summarizes recent (as of *SSI-02*, in some cases updated in November, 2002) results from the Super-Kamiokande and K2K experiments. The interpretation of Super-Kamiokande results on atmospheric and solar neutrinos provides strong evidence for neutrino oscillations, hence non-zero neutrino mass. While statistics are still limited, K2K data are consistent with Super-Kamiokande results on neutrino oscillations. The effort to reconstruct Super-Kamiokande following a cascade of phototube implosions in November, 2001 is described. Plans for future are also discussed.

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# 1 Introduction

This paper summarizes recent results from both Super-Kamiokande (SK) and the KEK to Kamiokande (K2K) long baseline experiment, KEK Experiment E362, which uses SK as its far detector. SK and K2K are independent experiments, operated by separate collaborations, although there is some overlap in membership (including the present author).

Both of these experiments focus on the study of neutrino oscillations among other topics. While the Standard Model of electroweak interactions has been tested with exceptional precision, it does not address the question of the origin of generations and their mixing. Neutrino oscillations imply that neutrinos are massive and that lepton flavors are not conserved quantum numbers. Experiments on atmospheric neutrinos (including SK) found a significant path-length dependent deficit in the flux of  $\nu_\mu$ .<sup>1,2,3</sup> Experiments on solar neutrinos (again, with SK prominently included) have similarly found evidence for an apparent deficit in the flux of  $\nu_e$ .<sup>4</sup> The interpretation of these results provides strong evidence for  $\nu_\mu \rightarrow \nu_\tau$  and  $\nu_\mu \rightarrow \nu_e$  oscillations.<sup>6,7</sup>

In the two flavor approximation, which as we will see is reasonable for SK and K2K data, for neutrino energy  $E_\nu(\text{GeV})$  and path length  $L(\text{km})$  from production point to detector, the oscillation probability can be written in terms of the mixing angle  $\theta$  and the difference of the neutrino masses squared  $\Delta m^2 (\text{eV}^2)$  as

$$P(\nu_\mu \rightarrow \nu_x) = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E_\nu)$$

For SK, the path length varies from about 20 km for neutrinos produced directly overhead, to about 13,000 km for upward going neutrinos, which have passed through the earth, while K2K has a fixed path length of 250 km.

In addition to the long-baseline analysis in K2K, the abundant neutrino interaction sample obtained in the near detector allows measurement of cross sections and other relevant data with better precision than many previous published results. Thus the near detector in K2K provides validation data for the Monte Carlo algorithm used to simulate neutrino interactions in SK and K2K.

## 2 Super-Kamiokande

SK is a water Cherenkov detector in the form of a cylinder with diameter and height both approximately 40 m, and total contained mass 50 ktons (Figure 1). The detector,

which was commissioned in early 1996, is located  $\sim 1000$  m or 2700 m.w.e. (meters water equivalent) underground at the Kamioka Observatory, which is operated by the Institute for Cosmic Ray Research of the University of Tokyo. The overburden is sufficient to reduce the abundant surface flux of downward-going muons to a level readily managed by the data acquisition system. The detector is divided by an optical barrier into a cylindrical primary detector region (the Inner Detector, or “ID”) and a surrounding shell of water approximately 2.5 m thick (the Outer Detector, or “OD”) serving as a cosmic-ray veto counter. Details of the detector and general data reduction procedures can be found in previous publications.<sup>2</sup>

The OD is instrumented with over 1800 20-cm diameter Hamamatsu photomultiplier tubes (PMTs). The ID was originally lined with over 11,000 inward-facing 50-cm PMTs, providing 40% photocathode coverage to efficiently detect few-MeV solar neutrinos. In November, 2001, about half of the 50-cm ID PMTs were destroyed in a cascade of implosions. Steps taken to rebuild and restart the detector will be described below. Data discussed in this paper were all taken during the period May, 1996 to July, 2001, with the original (SK-I) detector configuration. This period covered about 1489 live days of data-taking.

Events in SK are categorized as due to solar neutrinos (visible energy 4~20 MeV) or atmospheric neutrinos (visible energy above 100 MeV). This paper will focus on the atmospheric neutrino results; analyses of solar neutrino data have been published in detail elsewhere.<sup>5</sup> Atmospheric neutrino events are further divided into fully-contained (FC, with no significant activity in the OD), and partially-contained events (PC, with OD data consistent with exiting particles). Fully-contained atmospheric neutrino events are observed at an average rate of about 8.2 events per day, with about 0.6 PC events per day.

Contained events are tagged as muon-like or electron-like by a likelihood algorithm involving Cherenkov ring features, which was validated by a beam test at KEK before SK data taking began.<sup>8</sup> In simple terms, for the energy range of importance in SK, radiative losses are unimportant on average for muons, but dominant for electrons, resulting in significant showering (scattering and pair production). Thus muons leave sharp Cherenkov rings, while electrons leave fuzzier rings.

Another atmospheric neutrino event category is upward going muons (upmus), either stopping (OD data consistent with entering but no exiting particles), or through-going. The total cosmic-ray muon rate at Super-K is 2.2 Hz, of which a few percent are stopping muons, and the overwhelming majority are downward-going. Upmus can only

be produced by neutrinos interacting in the rock below SK, and on average represent the highest-energy sample of neutrinos, but must be carefully separated from a substantial background of near-horizontal downward-going muons. The trigger efficiency for a muon entering the ID with momentum more than 200 MeV/c is  $\sim 100\%$  for all zenith angles. Stopping muons with track length  $> 7$  m ( $\sim 1.6$  GeV) in the ID are selected for further analysis. Upmuons are observed at the rate of about 1.4 events per live day, of which about 0.3 per day are stopping tracks.

Details of the track reconstruction method and data reduction and analysis algorithms used in SK-I have been described in earlier papers.<sup>9</sup>

### 3 Results from SK-I atmospheric neutrino data

SK observes a significant deficit in muon-like atmospheric neutrino events, relative to expectation based on the best available simulations of cosmic ray interactions, and the subsequent production and propagation of neutrinos through the atmosphere. The deficit is strongly zenith-angle dependent, with a large effect for upward-going muon neutrinos and little or no deficit for downward going neutrinos of either flavor (Figure 2). At the energies considered, absorption in the earth is unimportant (and taken into account in the analysis). The zenith angle of arrival is of course correlated directly with the neutrino's flight path from its point of origin in the atmosphere. Downward-going neutrinos have travelled on the order of 20 km or less, while upward-going neutrinos have travelled up to 13,000 km through the earth. Thus neutrino oscillation is the leading suspect to explain the deficit.

Both the angular distributions of various event categories and the up/down ratio (Figure 3), which provides a relatively high-statistics integral measure of the effect, deviate from the no-oscillations expectation by many standard deviations, while agreeing well with internally consistent sets of oscillation parameters. Since electron neutrino distributions show no significant path-length dependence, it appears that SK observes only muon neutrino disappearance. The size and configuration of SK make it inefficient for identifying tau neutrinos, which promptly decay to muon and electron neutrinos. Muon neutrino disappearance, with observed electron neutrino rates approximately according to expectation, suggests that oscillations in the region of energy and path length probed by SK are dominated by 2-flavor  $\nu_\mu - \nu_{\tau}$  oscillations.

FC, PC and upmu data were reduced and analyzed by independent procedures and the fact that they give consistent results on best-fit oscillation parameters is signifi-

cant. For the combined data sets, the observed number of events, binned in energy and zenith angle, are compared to the simulation results, which assume no oscillations, and include allowances for systematic errors on the atmospheric neutrino production and propagation algorithms, as well as incorporating a large variety of calibration data and detector response measurements. The Monte Carlo (MC) results thus cover all known detector effects and efficiencies, while systematic error allowances for factors unamenable to calibration or direct correction are included as free parameters in the fitting procedure. A chi-squared minimization is used to find the allowed-region boundaries for selected confidence levels, on the 2-dimensional oscillation parameter space  $\Delta m^2, \sin^2(2\theta)$ . The latest released results for the combined analysis, covering the full SK-I period, are shown in Figure 4. As the plot shows, the atmospheric neutrino data suggest  $\{\Delta m^2, \sin^2(2\theta)\} = \{1.5 \sim 4 \times 10^{-3} \text{eV}^2, \sim 1.0\}$ , *i.e.*, full mixing.

While cosmological and big-bang nucleosynthesis considerations limit the number of light active neutrinos to about four,<sup>10</sup> LEP experiments<sup>11</sup> constrain the number of active neutrino flavors to  $2.99 \pm 0.01$ . Combined results from solar neutrino experiments, atmospheric neutrino experiments, and nuclear reactor neutrino oscillation experiments can accommodate a 3-flavor mixing scheme. However, in order to simultaneously accommodate results from the LSND short-baseline experiment,<sup>12</sup> it is necessary to assume a fourth type of neutrino, which must therefore be “sterile”: unable to interact with matter. Super-Kamiokande analyzed its atmospheric neutrino data to see if limits could be placed on the existence of sterile neutrinos, and found that they could be ruled out at the 99% confidence level, as described in detail elsewhere.<sup>7</sup>

## 4 K2K

Long-baseline experiments, in which a neutrino beam is directed from a particle accelerator laboratory to a distant, off-site detector, were first seriously proposed in the 1970s,<sup>13</sup> but K2K was the first such experiment to actually be commissioned and take data.<sup>14</sup> Several new long-baseline experiments are now under construction or in advanced planning stages,<sup>15,16</sup> including a next-generation version of K2K.<sup>17</sup>

Figure 5 shows the conceptual design of K2K. The KEK wideband neutrino beam is generated by directing a proton beam from the 12 GeV KEK Proton Synchrotron (PS) toward SK, including a  $1^\circ$  dip angle into the earth. Every 2.2 s, approximately  $6 \times 10^{12}$  protons in nine bunches are fast-extracted, making a  $1.1 \mu\text{s}$  beam spill. Following a 3-cm diameter Al target embedded in the front element of a 2-horn magnet system,

positive pions are focused into (and negative pions diverted from) a 200 m long decay pipe. A pion monitor (PIMON) employing a novel gas Cherenkov detector system can be inserted in the beamline to sample the secondary pion distributions.<sup>18</sup> Pion decays yield primarily muon neutrinos and muons. The muons are sampled by a muon monitor detector (MUMON) at the end of the decay tunnel, and then stopped by an iron and concrete beam dump and 70 m of earth, leaving a beam of muon neutrinos (98% pure) to make its way through the earth's crust to SK.

K2K originally used a 2 cm diameter Al target, for which the acceptance of the horns and decay pipe were designed. However, it was necessary to increase the target diameter after initial test runs revealed problems with the original design. This change reduced the efficiency of the horn system, lowering the net expected neutrino flux at SK for the integrated KEK beam allocation of  $10^{20}$  pot. Thus the total number of neutrino events expected in SK for the full exposure (in the absence of oscillations) will be about 200. After the latest run, which ended in July, 2001, the accumulated exposure was  $5.6 \times 10^{19}$  pot, or about 1/2 the expected total for the experiment. Possible extensions of the K2K program will be mentioned below.

The near detector suite (Figure 6) is located in an underground experimental hall 300 m from the production target, where neutrino interactions are observed by a set of detectors with complementary capabilities.

The K2K one kiloton water Cherenkov detector (1kt) uses the same technology and analysis algorithms as SK, the far detector. It has 680 50-cm photomultiplier tubes (PMTs) on a 70-cm grid lining a 8.6m diameter, 8.6m high cylinder. The PMTs and their arrangement are the same as in SK, and give the same fractional photocathode coverage (40%) as in SK-I. A scintillating fiber detector (SciFi),<sup>19</sup> consisting of 6 tons of target (water in thin Al tanks) interleaved with sci-fi tracking layers, allows discrimination between different types of interactions such as quasi-elastic or inelastic. Downstream of the SciFi there was a lead glass array for tagging electromagnetic showers, which was removed after the 2001 run. It will be replaced with a scintillator-bar array<sup>20</sup> (SciBar) to be installed during the summer 2003 beam shutdown. A muon range detector (MRD),<sup>21</sup> of total mass 915 tons, measures the energy, angle, and production point of muons from charged current (CC)  $\nu_\mu$  interactions.

K2K beam-induced events in SK are selected by comparing SK high energy event trigger times with the KEK-PS spill times via timestamps generated at both sites using identical Global Positioning System (GPS) clock systems.<sup>22</sup> Absolute times at the near and far sites are synchronized within about 100 nsec. The rate of background events

due to atmospheric neutrinos in the timing acceptance window of 1.5 microsec every 2.2 sec is negligible:  $\sim 10^{-3}$  events for the whole experiment.

The beamline was aligned by a GPS position survey.<sup>23</sup> The precision of this survey for defining the line from target to far detector is better than 0.01 milliradian, and the precision of construction for the near site beamline alignment is better than 0.1 mr. However, only about 3mr accuracy is required for beam pointing, since the predicted neutrino spectrum at 250 km is effectively constant over a diameter of nearly 1 km.

MUMON data are used to monitor the steering of the  $\nu_\mu$  beam in realtime. The muon yield is directly correlated with the horn-focused  $\nu_\mu$  beam intensity. MRD data provide a long-term stability check. The MRD event rate normalized to measured proton beam intensity is constant within errors, implying the  $\nu_\mu$  energy spectrum was stable throughout the K2K run period.

To predict the  $\nu_\mu$  beam characteristics at the far site, a normalization measurement at the near site and extrapolation from near to far are necessary. For event rate normalization, only the 1kt data are used, to take advantage of the cancellation of detector and analysis systematics in the far/near ratio. The average  $\nu_\mu$  event rate per proton on target (pot) in the 1kt detector is  $3.2 \times 10^{-15}$ .

For the near to far extrapolation, a beam Monte Carlo simulation is used, which is validated using the PIMON measurements of secondary pion momentum and angular distributions. This simulation is based on GEANT,<sup>24</sup> with detailed descriptions of materials and magnetic fields in the target region and decay volume. It uses as input a measurement of the primary beam profile at the target. Primary proton interactions on aluminum are modeled with a parameterization of hadron production data.<sup>25</sup> Other hadronic interactions are treated by GEANT-CALOR.<sup>26</sup>

Once the kinematic distribution of pions after production and focusing is known, it is possible to predict the  $\nu_\mu$  spectrum at any distance from the source. Correcting for efficiencies, relative target masses, and detector live times, the expected  $\nu_\mu$  signal at the far site can be estimated. Figure 7 shows the inferred  $\nu_\mu$  energy spectral shape at the near site along with the beam simulation result. As can be seen, the beam simulation is in excellent agreement with near detector data.

Data reduction algorithms similar to those used in atmospheric neutrino analyses at SK<sup>2,3</sup> are applied to select fully contained (FC) neutrino interactions. The number of Cherenkov rings and particle identification are reconstructed by the same algorithms as those used at SK,<sup>2</sup> and the event category definitions are also the same.

Since the measured uncertainty of the time synchronization accuracy for the two

sites is  $< 200\text{ns}$ , beam-induced events are selected by defining a  $1.5\mu\text{s}$  acceptance window surrounding the  $1.3\mu\text{s}$ -long spill time every 2.2 sec, offset by light-speed transit time to SK. Figure 8 shows the  $\Delta(T)$  distribution at successive stages in the SK data reduction. After various cuts used to select high energy events, a clear, isolated peak in time appears, correlated with the predicted arrival of the neutrino beam from the KEK-PS.

The K2K oscillation analysis uses two independent approaches, which can then be combined in a global likelihood fit for oscillations parameters. First, the total number of beam-induced events in SK is compared to the expected number of events in the absence of oscillations, taking into account the coordinated livetimes of SK and the various near detectors, and the corresponding integrated beam intensity (as measured by the number of protons on target delivered during simultaneous detector livetimes). This provides a relatively high statistics integral measure of oscillation effects, and allows a test of the no-oscillation hypothesis with maximum significance given the limited data.

Second, the shape of the neutrino energy spectrum is a sensitive indicator of oscillation effects. Since path length  $L$  is fixed in K2K, any dependence on  $L/E$  reveals itself in distortions of the neutrino energy spectrum.

The predicted number of SK events in the absence of oscillations, for the running period discussed here, is  $80.1^{+6.2}_{-5.4}$ . With 56 observed FC events in SK, the probability that the observed number is due to chance fluctuations is less than 1.3%. Figure 9 compares the observed far detector energy spectrum in comparison with expectation for the no oscillations hypothesis, and the best-fit oscillation parameters. Putting together the spectrum shape and number information in a combined fit, the no-oscillations hypothesis can be rejected with 99.3% confidence. Figure 10 shows the allowed region in parameter space; these results indicate  $\Delta m^2 = 1.5 \sim 4 \times 10^{-3} \text{eV}^2$ , with large mixing angle, quite consistent with the SK allowed region.

While statistics are still limited, K2K data collected during the SK-I run are evidently consistent with SK results on atmospheric neutrino oscillations. A paper submitted at time of writing<sup>27</sup> describes in more detail the methods used to obtain these results. Additional data will be collected starting in January, 2003, and another run is planned for 2004. Further data taking may be possible depending upon the interplay between KEK-PS operations and construction of the new 50 GeV accelerator at the Japan Atomic Energy Research Institute (JAERI) site, as described below.



## 5 Deconstruction and Reconstruction of Super-K

As noted, a cascade of PMT implosions in November, 2001 destroyed over half of the PMTs in the SK detector. Thanks to a prompt response by agencies supporting the experiment (and intense effort by many people), it was possible to begin reconstruction a few months thereafter, with an aggressive timetable calling for restarting the experiment in December, 2002. By the end of 2001, an investigation had been conducted, causes identified, and a plan for protecting against future occurrences developed and tested.

SK-II ID PMTs are contained in plastic housings, with a clear acrylic dome over the photocathode, and the tube body and base enclosed in a PVC shell. The acrylic domes have a negligible (few percent) effect on photon detection efficiency, since they are only a few mm thick and their index of refraction is close to that of water. The housings are not pressure vessels, but are simply intended to slow down the influx of water in case of implosion, eliminating the shock wave effect that initiated the cascade of implosions in late 2001. Destructive testing was performed at 30 m water depth, with PMTs closely spaced as in SK-I, both with and without housings, and performance of the protection scheme was confirmed. Tests showed that implosion of a 50-cm PMT will not harm its nearest neighbors with the housings in place. Of course, during SK-II the approximately doubled spacing between ID PMTs will provide an additional margin of safety.

Since it was not possible to procure a full complement of 50-cm PMTs promptly, the resurrection of SK will proceed in two stages. SK-II, scheduled to begin data taking in December, 2002, will have approximately 50% ID PMT coverage relative to SK-I. Surviving PMTs and about 1000 new PMTs were redistributed around the ID, with roughly every other PMT site occupied. The reduction in photocathode coverage will raise the effective threshold for solar neutrinos, but simulation studies indicate that data from high energy triggers (atmospheric neutrinos, upmus and K2K beam neutrinos) will suffer only minor reductions in angular and energy resolution. By 2005, enough 50-cm PMTs to will be available to restore full occupancy in the ID; this upgrade will initiate the second stage of revival, SK-III.

Progress in carrying out these plans has been rapid and efficient. By the end of March, 2002, debris had been cleared and reconstruction work begun. All PMTs were removed before starting reconstruction. Sufficient spares were available to replace all lost 20-cm OD PMTs, so the OD was restored fully. Repairs to the bottom and side

PMTs were completed by September, 2002, and filling with water began. The detector was operated throughout the filling period, except for brief intervals for calibration studies, to maintain a supernova watch with the available volume. By the time of writing (November, 2002), the SK tank had been refilled without incident, and final work on the top layer of PMTs was being completed. Thus SK is on track to begin data taking by the time the next K2K beam is available. Beam tuning at KEK will begin in mid-December, 2002.

## 6 Future

K2K will take data throughout 2003, except for the usual KEK-PS summer beam shutdown. By 2005, it is expected that K2K will have received its allocated beam exposure, and KEK beamline components will need to be moved to the new 50 GeV accelerator under construction at the JAERI site at Tokaimura, about 130 km NE of Tokyo. The new high-intensity accelerator, recently officially renamed J-PARC (Japanese Proton Accelerator Research Complex) but still commonly referred to by its original acronym “JHF” (Japan Hadron Facility), will deliver first beam in 2007. By then, SK will have been re-equipped with a full complement of PMTs.

At that time, interest will be focused on a second-generation long-baseline experiment, with working title “JHF-Kamioka”. Preliminary steps have been taken to organize a broadly-based international collaboration. Initial designs for a narrow-band neutrino beamline, and conceptual designs for a near detector configuration have been developed and are under discussion by interested physicists.<sup>17</sup> The JHF neutrino beam will deliver more events per unit time to SK than the KEK-PS beam by about two orders of magnitude. Thus JHF-Kamiokande should be able to fully explore the parameter space defined by SK and K2K with high statistics within a few years. The baseline from Tokaimura to SK is 295 km, only slightly larger than for K2K.

The next goal for long-baseline neutrino physics will be to explore CP violations, requiring much higher statistics. For this task, SK is too small to contribute significantly in reasonable time, even with the JHF beam. Preliminary plans, still at the conceptual level, have been developed for “Hyper-Kamiokande”, a 1-megaton water Cherenkov detector.<sup>29</sup> The SK geometry cannot simply be scaled up, due to fundamental engineering limits on cavity size in rock, but a gallery of adjacent units could be constructed. Also, the present SK site cannot be used, due to limitations on road access to the Mozumi mine. However, a site close to the town of Kamioka, where the mining

company has its main facilities, could be used. The neutrino beam will be designed to be broad enough to cover both sites with its stable central region.

## 7 Conclusion

There is growing consensus that there are probably only three low-mass neutrinos (unless Mini-Boone confirms LSND results<sup>28</sup>), with the lighter pair of eigenstates nearly degenerate and the third state separated in mass. As a result, we observe two mass-squared differences,  $\Delta m_{12}^2$  and  $\Delta m_{23}^2$ , with different magnitudes. The larger  $\Delta m^2$  can be identified with the two-state  $\nu_\mu - \nu_\tau$  mixing observed in atmospheric oscillations, while the smaller  $\Delta m^2$  applies to the  $\nu_\mu - \nu_e$  mixing observed in solar neutrino experiments such as SK and SNO. The mass hierarchy, *i.e.*, whether the third state lies above or below the close pair, is yet to be determined. However, exploration of the neutrino sector is far from complete, and second generation experiments such as MINOS, JHF2K, ICARUS, *et al* have much to do. New experiments on mixing schemes, mass hierarchy, matter effects, and perhaps CP violations will keep the field lively for some time to come. Interested students are invited to join the fun!

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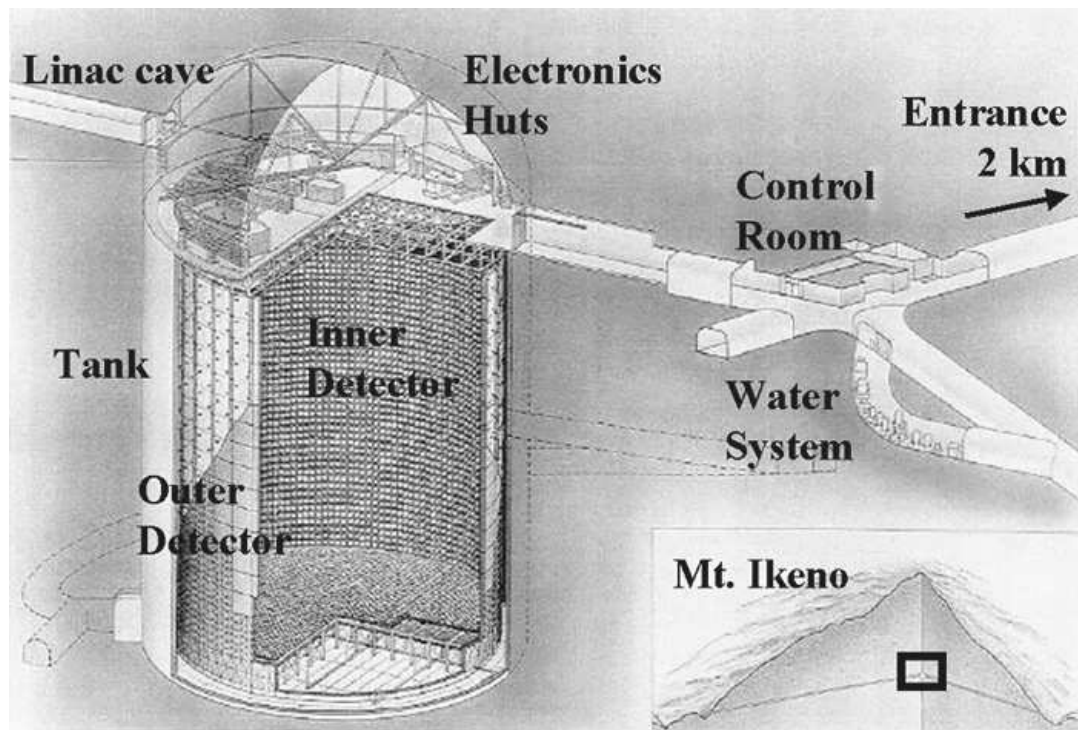


Figure 1: The Super-Kamiokande underground water Cherenkov detector, located near Higashi-Mozumi, Gifu Prefecture, Japan. Access is via a 2 km long truck tunnel. Inset shows location of detector area within the overburden.

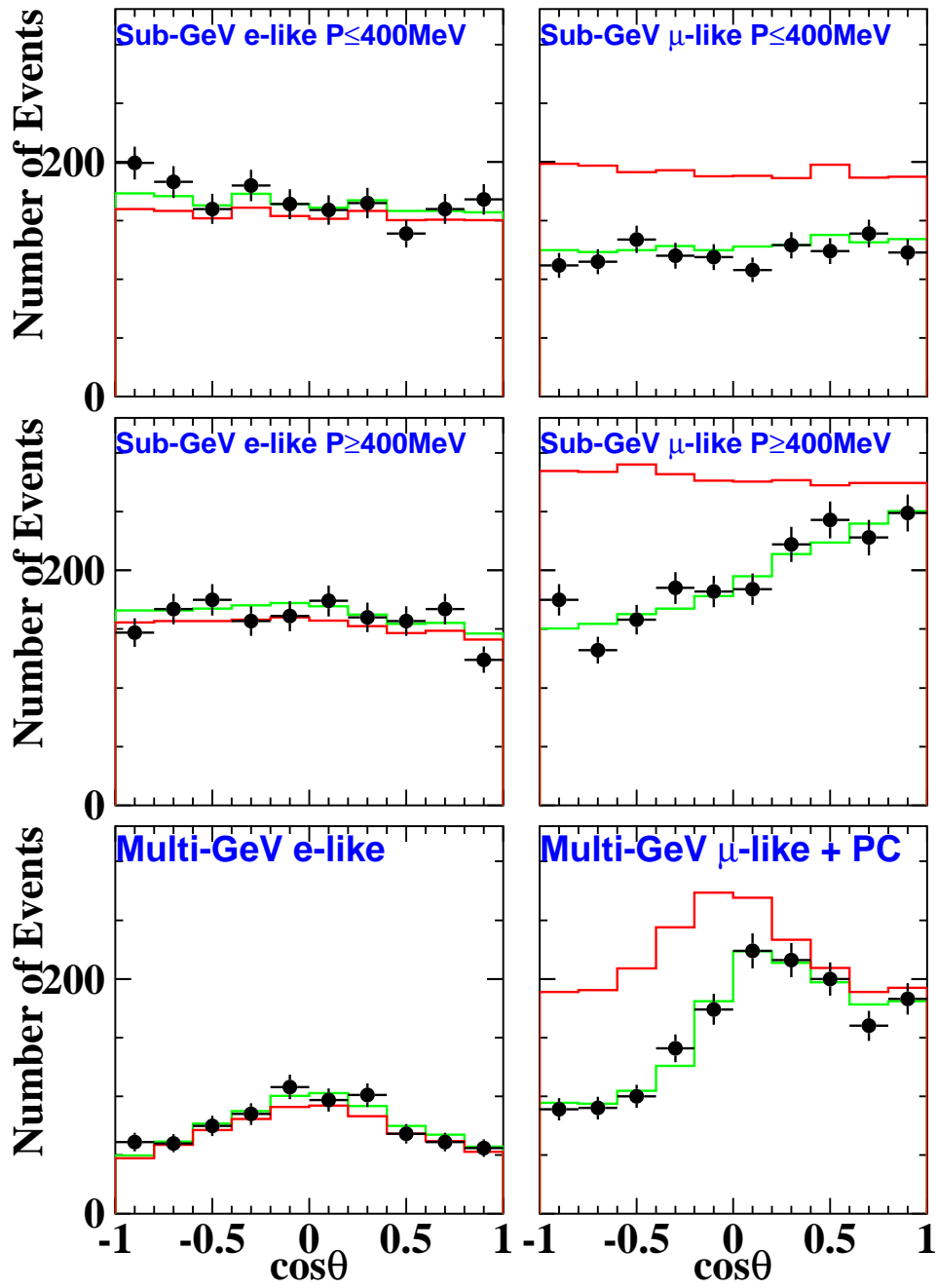


Figure 2: Atmospheric neutrino zenith angle distributions in SK (data points). Electron-like events agree with expectation for no oscillations (darker histogram), but muon-like events show a large deficit for upward-going neutrinos (i.e., those with long path lengths). Lighter histogram shows expectation for best-fit oscillation parameters.

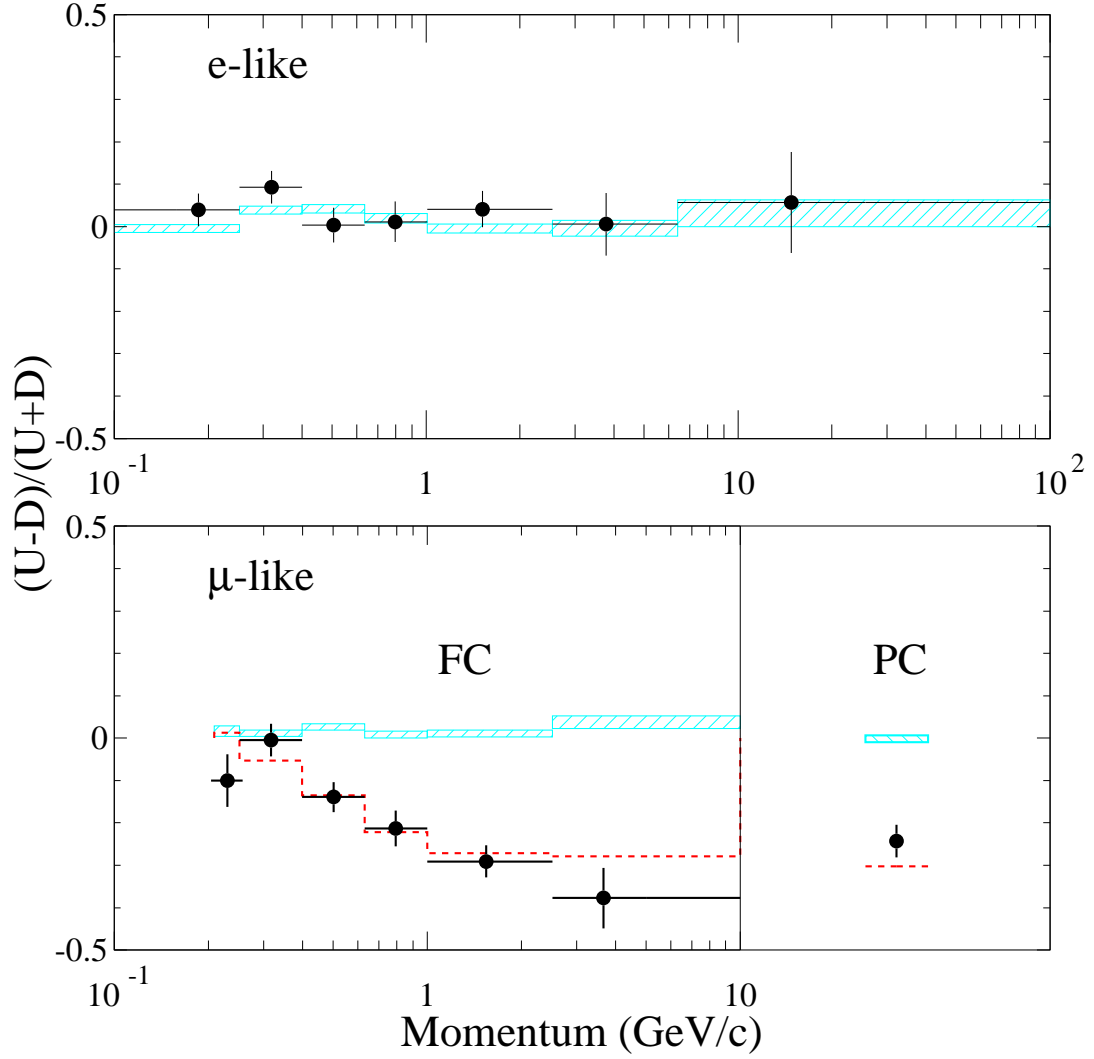


Figure 3: Up/Down ratio for atmospheric neutrino events in SK, an integral representation of the angular distributions. A highly significant deficit relative to expectation for no-oscillations is seen for muon-like events while electron-like events are consistent with expectation. Dashed histogram in lower plot shows expectation for best-fit oscillation parameters.



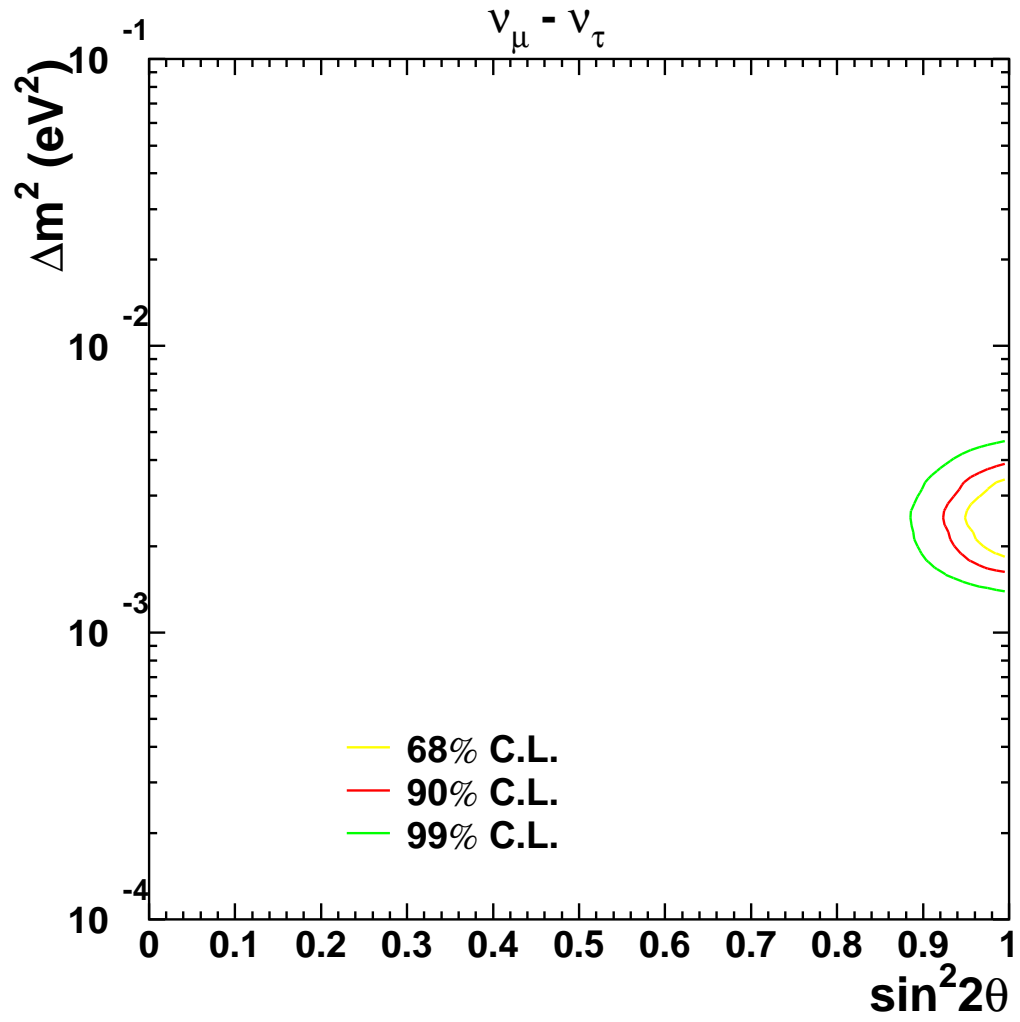


Figure 4: Allowed region in 2-flavor oscillation parameter space from combined analysis of FC, PC and upmu events in SK. The fit shown was constrained to occupy only the physical region ( $\sin^2 2\theta \leq 1.0$ ); a fit without this constraint gives very similar results within the physical region.

## K2K Overview

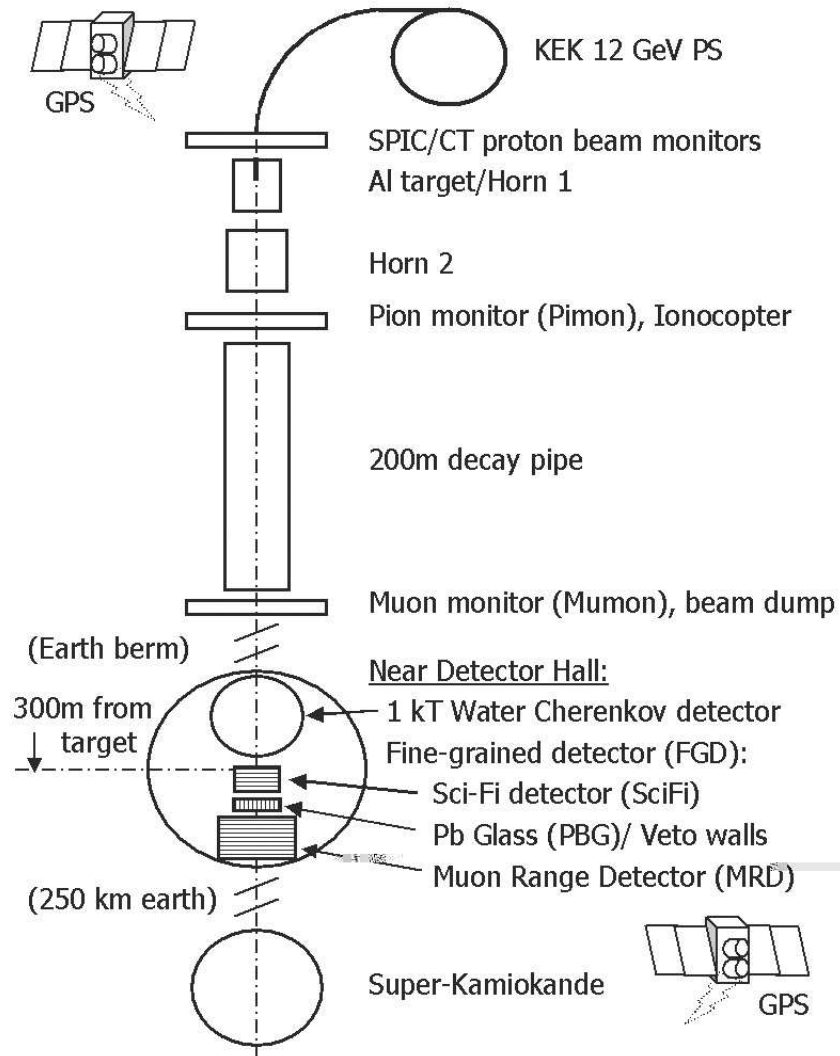


Figure 5: Overview of K2K, showing cartoon view of important elements: beam-line, beam monitors, near detector, far detector, and GPS time synchronization system. Beam spill times are timestamped at KEK using a GPS clock system. The list of spill times is transmitted by Internet link to SK, and used to select events, which are timestamped by an identical GPS clock system, before they leave the offline processing stream. SK triggers within a  $1.5 \mu\text{sec}$  acceptance window around the expected arrival time of beam neutrinos are analyzed as K2K events.

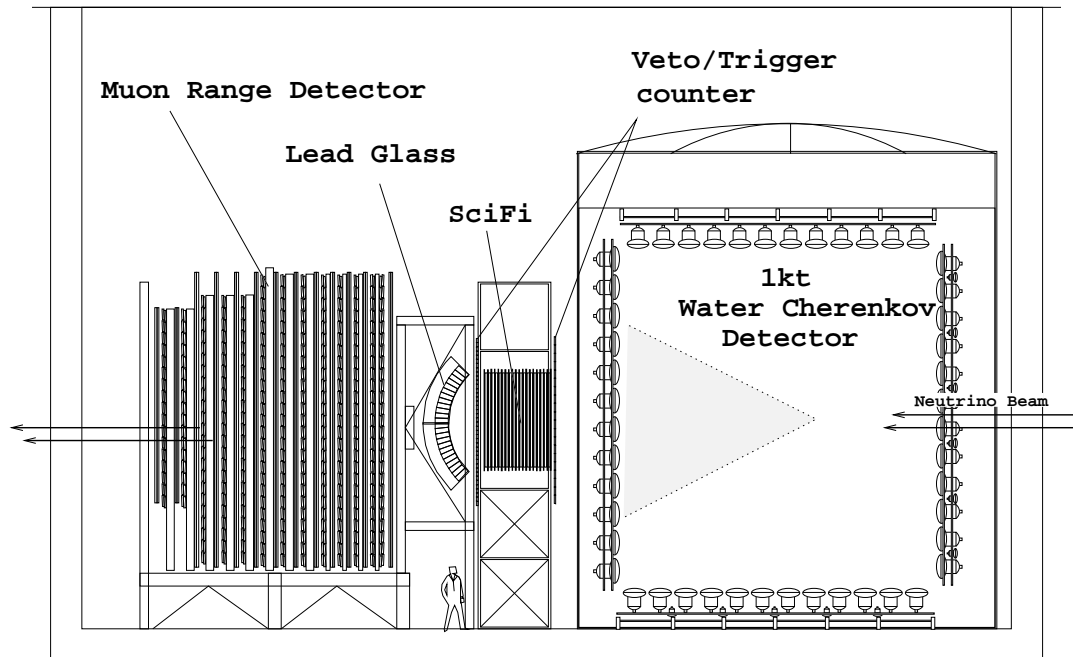


Figure 6: Near detector components at KEK. The 1kt Water Cherenkov detector employs identical PMTs and geometry as SK. The SciFi detector, with water target tanks, provides detailed tracking for analysis of quasi-elastic and inelastic events. The Lead Glass detector was removed in 2001 and will be replaced with another tracking detector.<sup>20</sup> The Muon Range detector identifies and measures the momentum of muons; accumulated data provide information on beam stability.

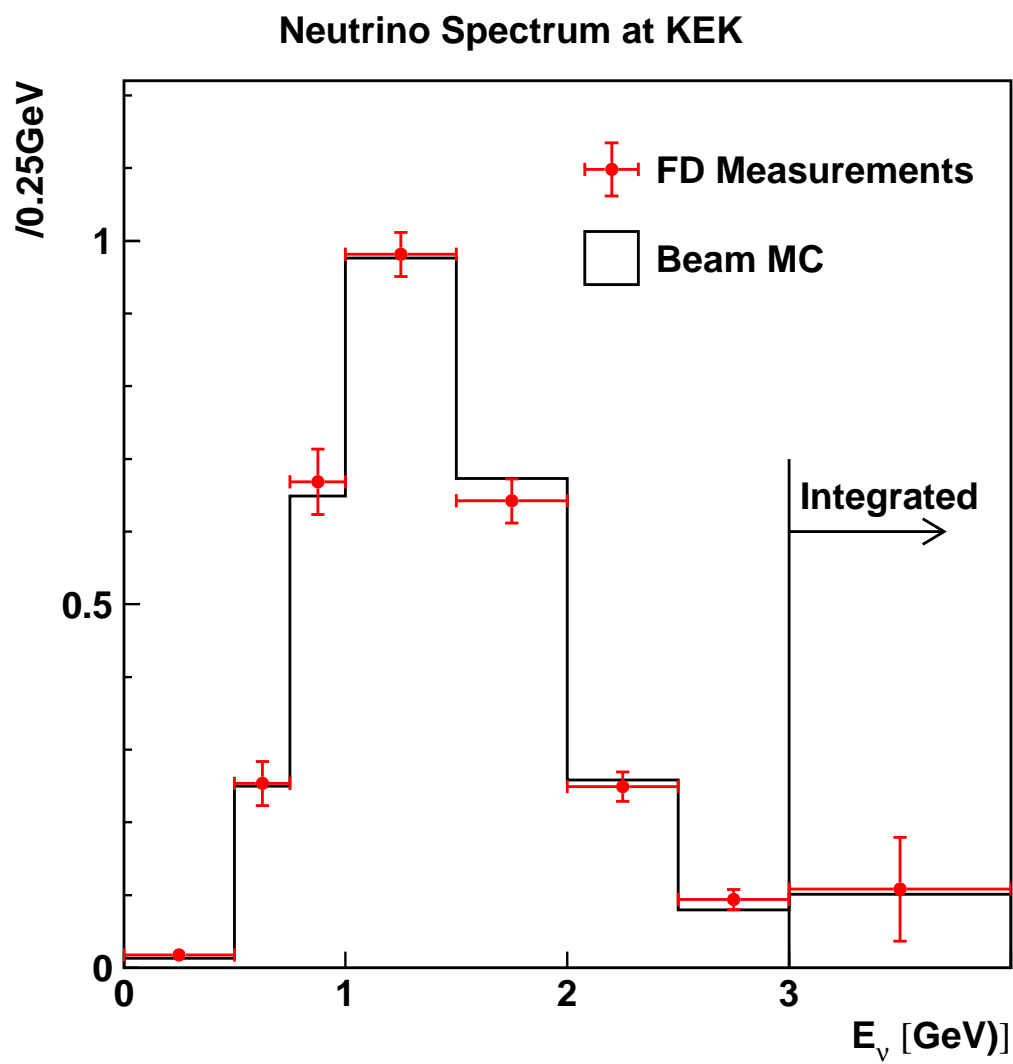


Figure 7: K2K neutrino beam energy spectrum, as inferred from front (near) detector data, compared to the beam Monte Carlo.

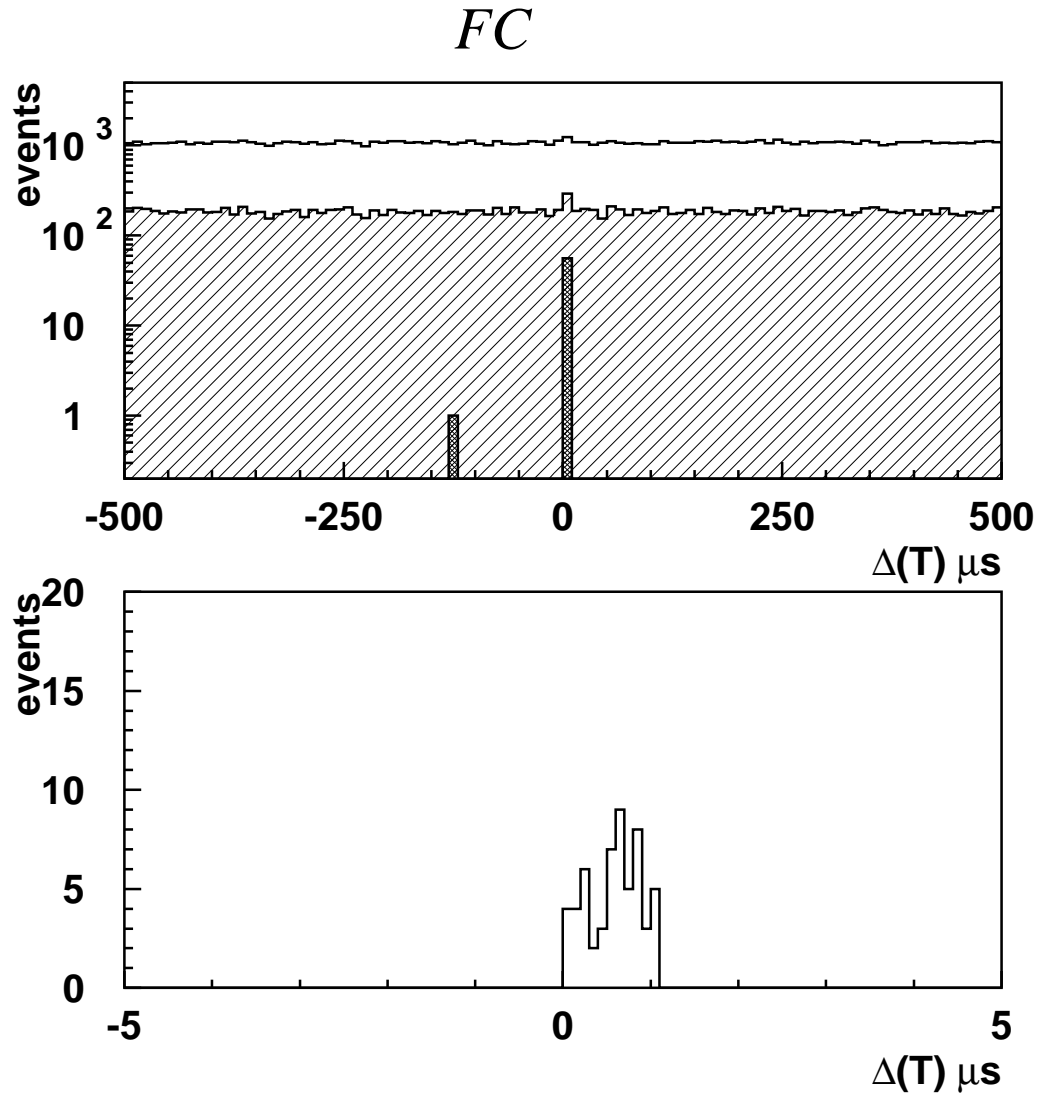


Figure 8: Time difference between triggers at SK and expected time of beam neutrino arrival, based on spill time data from KEK. Upper histograms show various stages in the data reduction; after the required fiducial volume and energy cuts are imposed, it can be seen that a sharp peak appears at 0, relative to the  $1.5\mu\text{sec}$  timing acceptance window. The nearest random background event (out of the entire data sample) can be seen over  $100\mu\text{sec}$  out of time. Lower plot shows a closeup of the region around  $\Delta T = 0$ .

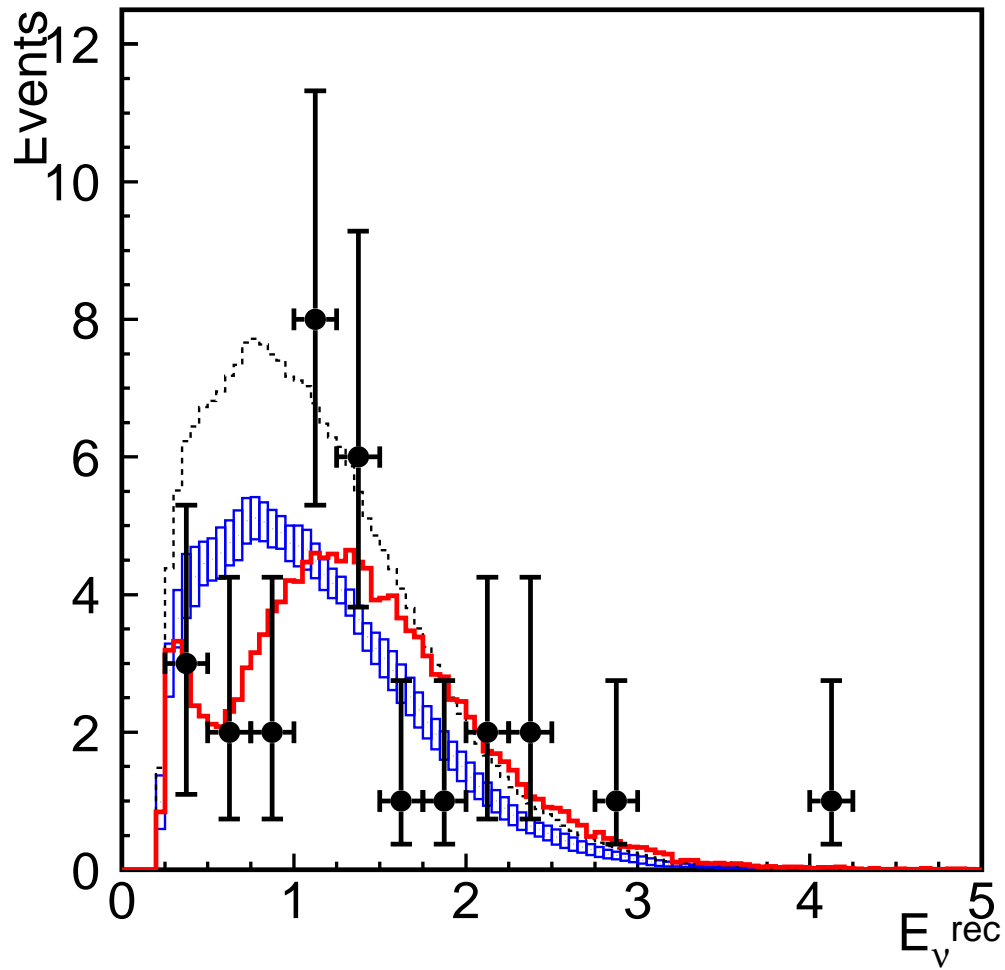


Figure 9: Energy spectrum of the K2K events at SK. Predicted spectrum obtained by extrapolation of near detector results is compared with observed SK data. Points with error bars are data. Boxes: expectation for no oscillations, showing systematic errors, normalized to the number of observed events. Solid: spectrum for best-fit oscillation parameters, also normalized to the number of observed events. Dashed line: expectation for no oscillations, normalized to *expected* number of events.

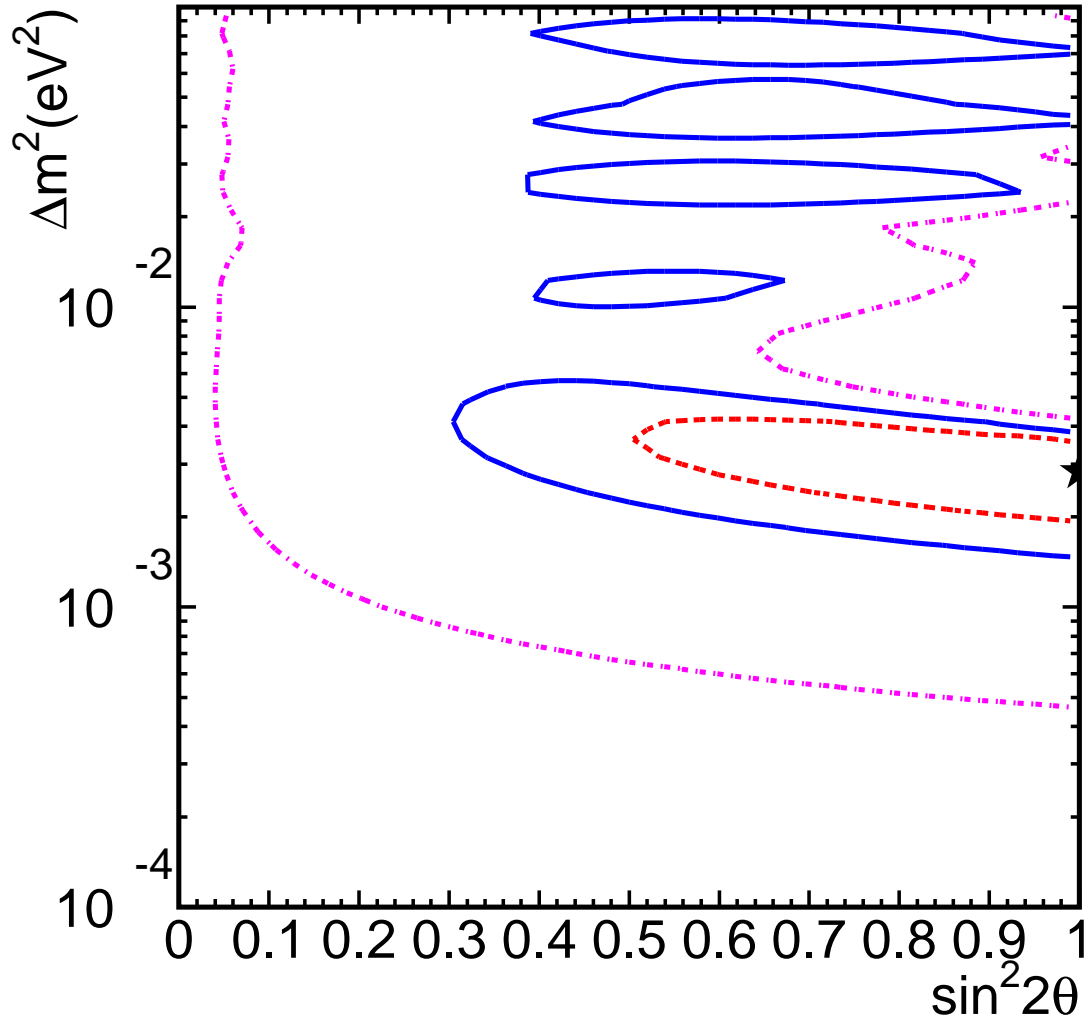


Figure 10: Allowed region in 2-flavor ( $\nu_\mu \rightarrow \nu_\tau$ ) parameter space from K2K combined analysis of the number of events and energy spectrum data. Solid line indicates 95% CL contours; dashed line: 68%; dot-dashed line: 99%; star indicates best-fit point. Compare to Figure 4.